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SUMMARY OF THE DIGITAL ADAPTIVE FILTER, DIGITAL POLYNOMIAL FILTER AND SPECIFICATION SET CONTROL TECHNIQUES APPLIED TO LARGE LAUNCH VEHICLES

by John Zaborszky and William J. Luedde

Prepared under Contract No. NAS 8-11418 *by*
MCDONNELL AIRCRAFT CORPORATION
St. Louis, Mo.
for George C. Marshall Space Flight Center

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SET CONTROL TECHNIQUES APPLIED TO LARGE LAUNCH VEHICLES

By Dr. John Zaborszky and William J. Luedde
McDonnell Aircraft Corporation
St. Louis, Missouri

FOREWORD

This report is an abstract of a final report (Reference 1) prepared by the McDonnell Aircraft Corporation, St. Louis, Missouri, under NASA contract NAS8-11418, "Control Techniques for Large Launch Vehicles."* The work was administered under the direction of the Astrodynamics Division of the Aero-Astrodynamics Laboratory of the George C. Marshall Space Flight Center.

The study presented herein began in July 1964 and was concluded in September 1965, and represents the efforts of the Engineering Technology Division of McDonnell. The chief contributors were Dr. John Zaborszky (Consultant), Mr. William J. Luedde (Group Engineer), Mr. David F. Brown (Engineer), Dr. Roger L. Berger, and Mr. Kenneth Kessler. The latter two were with Washington University, participating under a subcontract from McDonnell.

* This report, McDonnell Report B897, is available to qualified NASA requesters through:
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INTRODUCTION

As launch vehicle size has increased, major control problems have been encountered which are largely attributable to potential oscillatory conditions caused by structural elasticity and fuel slosh. For large launch vehicles, the frequency characteristics of these phenomena interact both with nominal rigid body control frequencies and with one another. An additional but usually minor control problem is the fact that these vehicles are also aerodynamically unstable.

Working under the direction of the Astrodynamics and Guidance Theory Division at Marshall Space Flight Center, McDonnell has performed a study of the application of digital filter techniques to the control problems of two large launch vehicles. In applying these techniques, the objective is to insure system stability and to provide desirable response characteristics for these vehicles, whose bending and slosh mode frequencies approach those of the control mode.

Two separate and largely independent sets of performance requirements led to two different digital solutions which may be applied either independently or jointly. The first requirement, typical for launch vehicles, was to minimize the vehicle angle of attack and loads when the vehicle is subjected to wind disturbance inputs. (Precise following of the guidance commands in this case is not critical as long as the total vehicle loads are sufficiently small and the terminal conditions are adequately met.) A digital polynomial filter inserted in the acceleration or angle-of-attack feedback provided a solution to this problem.

The second requirement was concerned with the ability of the vehicle to precisely follow guidance commands assuming the vehicle loads are within acceptable limits. The digital adaptive filter applied in the forward loop of the vehicle control system provided a solution. In addition to developing digital filter solutions to these problems, a somewhat nonrelated technique of linear system design was briefly investigated. Known as "specification set," it aims to provide a method of designing linear systems to performance specifications without the customary cut-and-try procedures.

The complete results of these studies are presented in detail in Reference 1. This summary, abstracted from the Reference 1 report, contains a brief description of the approaches used toward solving the control problems and discusses the significant results obtained.

VEHICLE CONTROL IN THE PRESENCE OF WIND DISTURBANCES

When a large launch vehicle employing conventional attitude plus attitude-rate feedback passes through severe wind profiles, it may develop an angle of attack approaching or in excess of that established by structural limits. Also, engine deflection limits may be approached as the vehicle attempts to maintain its commanded attitude. The structural loads and the engine deflection angles in the wind environment may be reduced by the use of either acceleration or angle-of-attack feedback in the vehicle control system. The addition of this type of feedback will cause the vehicle to turn into the wind, reducing the structural loads and engine deflection angles at the expense of an inaccuracy in maintaining the desired vehicle attitude. This form of control, as studied and developed by NASA, employs the "drift minimum" control principle described in Reference 2. The uncompensated use of angle of attack or acceleration feedback, however, will usually cause a control system instability to occur at the body bending modes, since one or more of the bending mode signal components is likely to be of a destabilizing phase. Since the principal function of the acceleration or angle of attack feedback is to pass the gross variations of windshear which are low in frequency compared to body bending frequencies, it was considered feasible to insert a low pass filter in this feedback path to stabilize the vehicle and at the same time respond to the basic wind inputs. The performance of a digital polynomial filter was studied and evaluated, and it was then compared with the performance of a conventional linear low pass filter.

The digital polynomial filter stores equally spaced samples of its input signal taken over some fixed time interval and fits a low degree (zero, first, or second) polynomial to these samples in a mean square sense. It then generates an output computed for the present time from the fitted polynomial. Since the degree of the polynomial is low, its ability to follow signals with wavelengths of a fraction of the time interval is limited. Hence, higher frequencies are attenuated and low pass filtering results. The amplitude and phase characteristics of the zero order polynomial digital filter are shown in Figures 1 and 2. The asymptotes of a first order linear filter response are also plotted in Figure 1 and are shown to form an envelope of the digital polynomial filter amplitude response. The phase angles of the digital polynomial filter shown in Figure 2 are quite different from a linear filter, however, and are in general much larger than those of a first order linear filter.

Summary of Studies Performed

To evaluate the merits, limitations, and feasibility of the digital polynomial filter as a means of control while crossing atmospheric areas of severe windshear, two study vehicles were represented in great detail by both hybrid and pure digital simulation, including as many as three slosh modes and four body bending modes with their associated cross couplings. Detail description of the test vehicles and the control system simulations is given in Reference 1*. It is sufficient to say here that Vehicle I is typical of the latest boosters now in the preliminary phase of hardware test of their major components, and Vehicle II is representative of boosters being considered for the future. The simulation tests of the digital polynomial filter were

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*In addition to the description of the digital and hybrid simulations presented in Reference (1), the IBM 7094 digital computer program listing and math flow are being transmitted to the contracting agency.

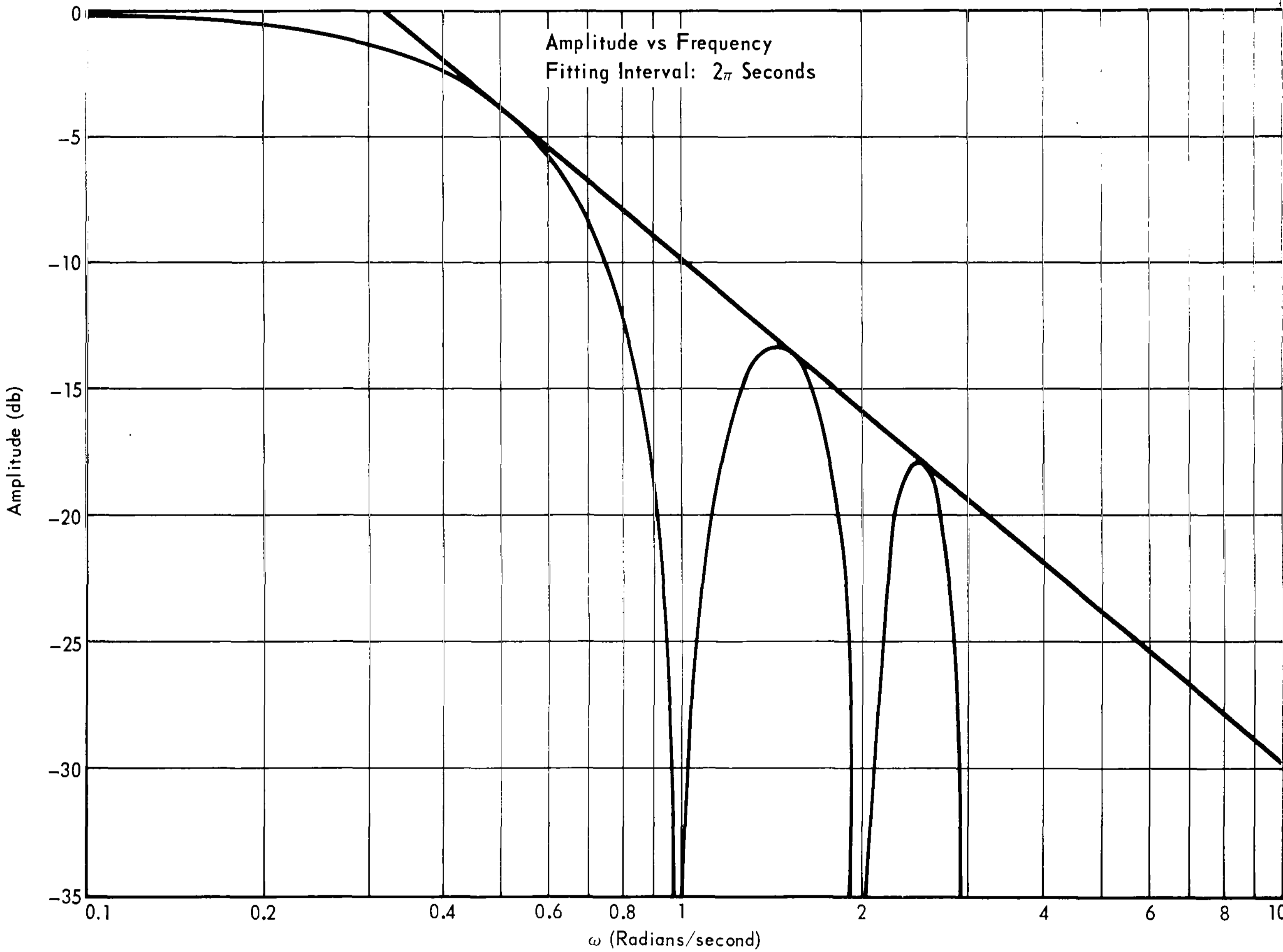


Figure 1 Frequency Response of One Parameter Polynomial Fitting (A_0)

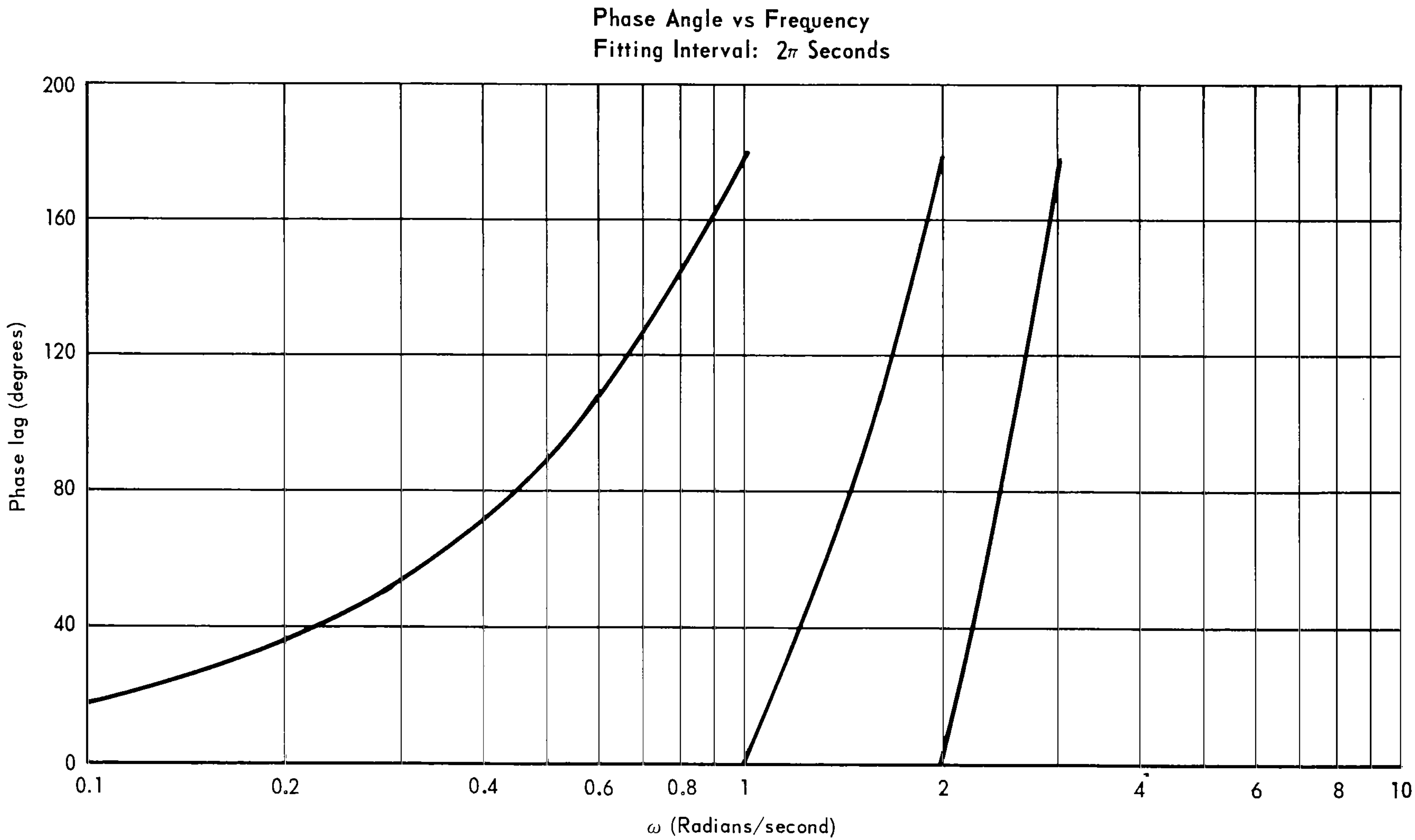


Figure 2 Frequency Response of One Parameter Polynomial Fitting (A_0) (Cont.)

restricted to the maximum q flight condition since this coincides with the areas of maximum windshear. Several hundred simulated runs were taken to establish the quality of performance achieved by the use of the digital polynomial filter under "nominal" conditions as well as the sensitivity of the filter performance to the variables of the environment. The specific areas of study included:

(a) Sensitivity to general control parameters

  (1) Acceleration (or angle of attack) feedback gain
  (2) Attitude and attitude rate feedback gains
  (3) Stabilizing network compensation for the bending and slosh modes
  (4) Compensation for improvement of steady state command response

(b) Sensitivity to digital polynomial filter parameters; degree of polynomial, sampling rate, number of samples

(c) Sensitivity to variations of booster parameters such as aerodynamic derivatives, bending frequencies, etc.

(d) Sensitivity to variations in the wind profile.

Abstract of Test Results

The performance of study Vehicles I and II subjected to a synthetic wind profile disturbance input were investigated for two control schemes: The first provided attitude control using attitude and attitude rate feedbacks; and the second provided drift minimum control using attitude, attitude rate, and acceleration (or angle of attack) feedbacks. Studies of the drift minimum control system were made to determine the effects on the system performance of the digital polynomial filter, a linear low pass filter, or no compensation at all in the acceleration feedback path. The configurations of the control systems studied are presented in detail in Figure 3. The system gains and forward loop compensation shown in Figure 3 were determined from the simulation studies to give the best compromise for the stability of the body bending and fuel slosh modes and the response of the vehicle to command and disturbance inputs.

Figures 4 through 9 present time history responses to a wind disturbance input of various parameters of study Vehicle I. These figures show the vehicle response without acceleration feedback (Figures 4 and 5) and then with acceleration feedback, first without (Figures 6 and 7) and then with (Figures 8 and 9) the digital polynomial filter. Figures 10 and 11 show the response characteristics of study Vehicle II with the digital polynomial filter (Figure 10) and with a linear lag network (Figure 11) in the acceleration feedback path.

	Vehicle I		Vehicle II	
	(Design I.1)		(Design II.1)	(Design II.3)
	Attitude and Attitude Rate Feedback	Attitude, Attitude Rate, and Acceleration Feedback	Attitude, Attitude Rate, and Acceleration Feedback With Digital Polynomial Filter	Attitude, Attitude Rate, and Acceleration Feedback With Linear Low-Pass Filter
Compensation network	$\frac{5.2\,(10S+1)\,[(S+1)^2+14^2]}{(S+4)\,(50S+1)\,(S+16)^2}$	$\frac{5.2\,(10S+1)\,[(S+1)^2+14^2]}{(S+4)\,(50S+1)\,(S+16)^2}$	$\frac{.117\,(10S+1)}{(50S+1)}\left[\frac{(S+5.5)^2+9.2^2}{(S+5.6)\,(S+2.4)}\right]$	$\frac{.08\,(10S+1)}{(50S+1)}\left[\frac{(S+9.2)^2+9.1^2}{(S+5.6)\,(S+2.4)}\right]$
System gain	1.8	1.8	2.2	2.2
Attitude feedback gain	1.0	1.0	1.0	1.0
Attitude rate feedback gain	5.0	5.0	5.0	5.0
Acceleration feedback compensation	0	.072	.095	$\frac{.095}{1+10S}$
Angle of attack feedback gain	0	0	0	0

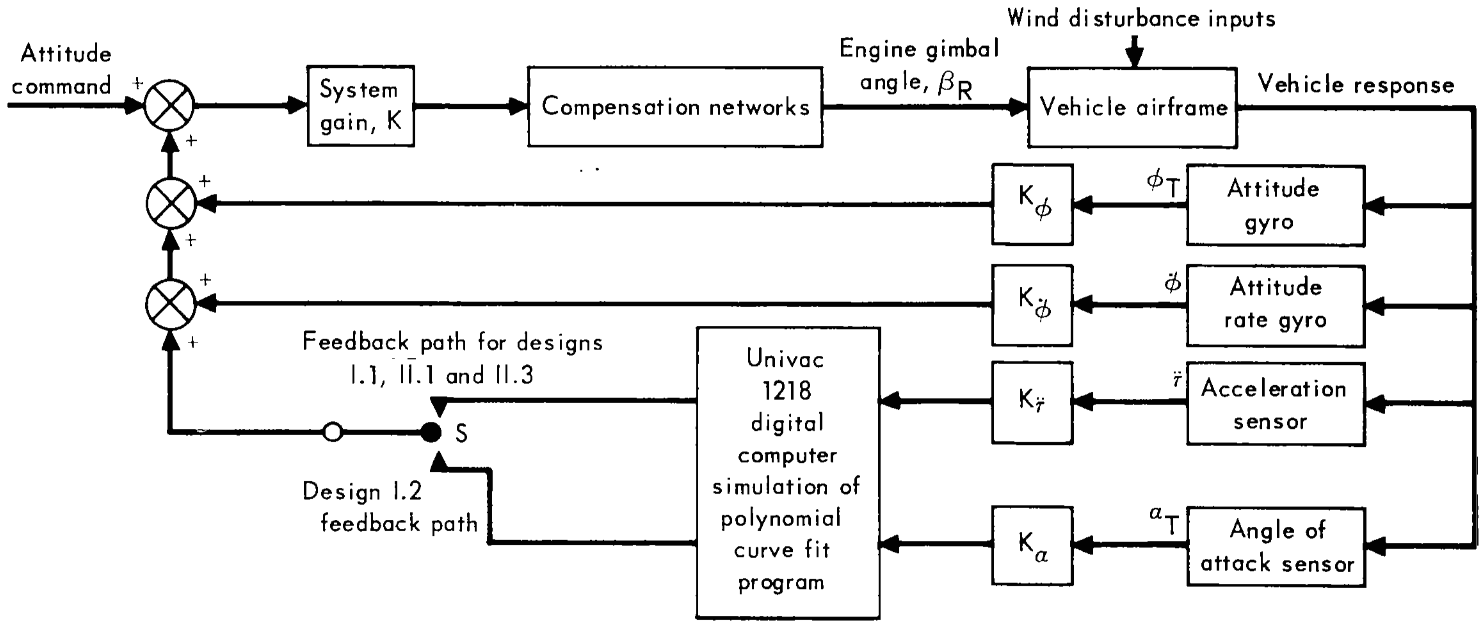


Figure 3 Block Diagram of Study Vehicles I and II Control Systems With Digital Polynomial Filter

1. Flight condition, maximum q
2. Body bending and fuel slosh, out
3. Control system design, 1.1
4. Forward loop gain, $K = 1.8$
5. Position feedback gain, $K_{\phi} = 1.0$
6. Rate feedback gain, $K_{\dot{\phi}} = 5.0$

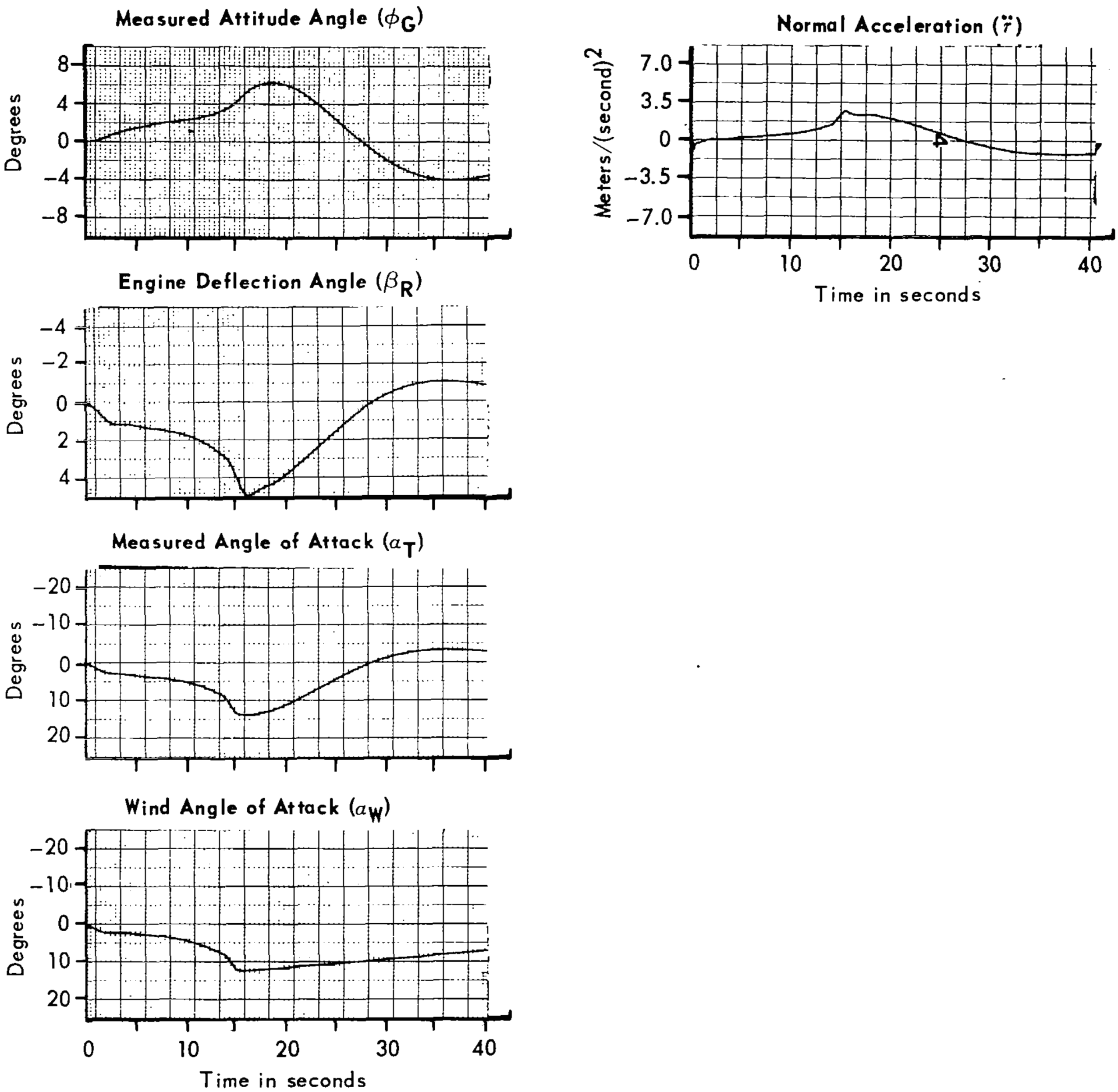


Figure 4 Wind Response of Study Vehicle No.1 With Attitude and Attitude Rate Feedback

1. Flight condition, maximum q
2. Body bending and fuel slosh, in
3. Control system design, 1.1
4. Forward loop gain, $K = 1.8$
5. Position feedback gain, $K_{\phi} = 1.0$
6. Rate feedback gain, $K_{\dot{\phi}} = 5.0$
7. Acceleration feedback gain, $K_{\tau} = 0$

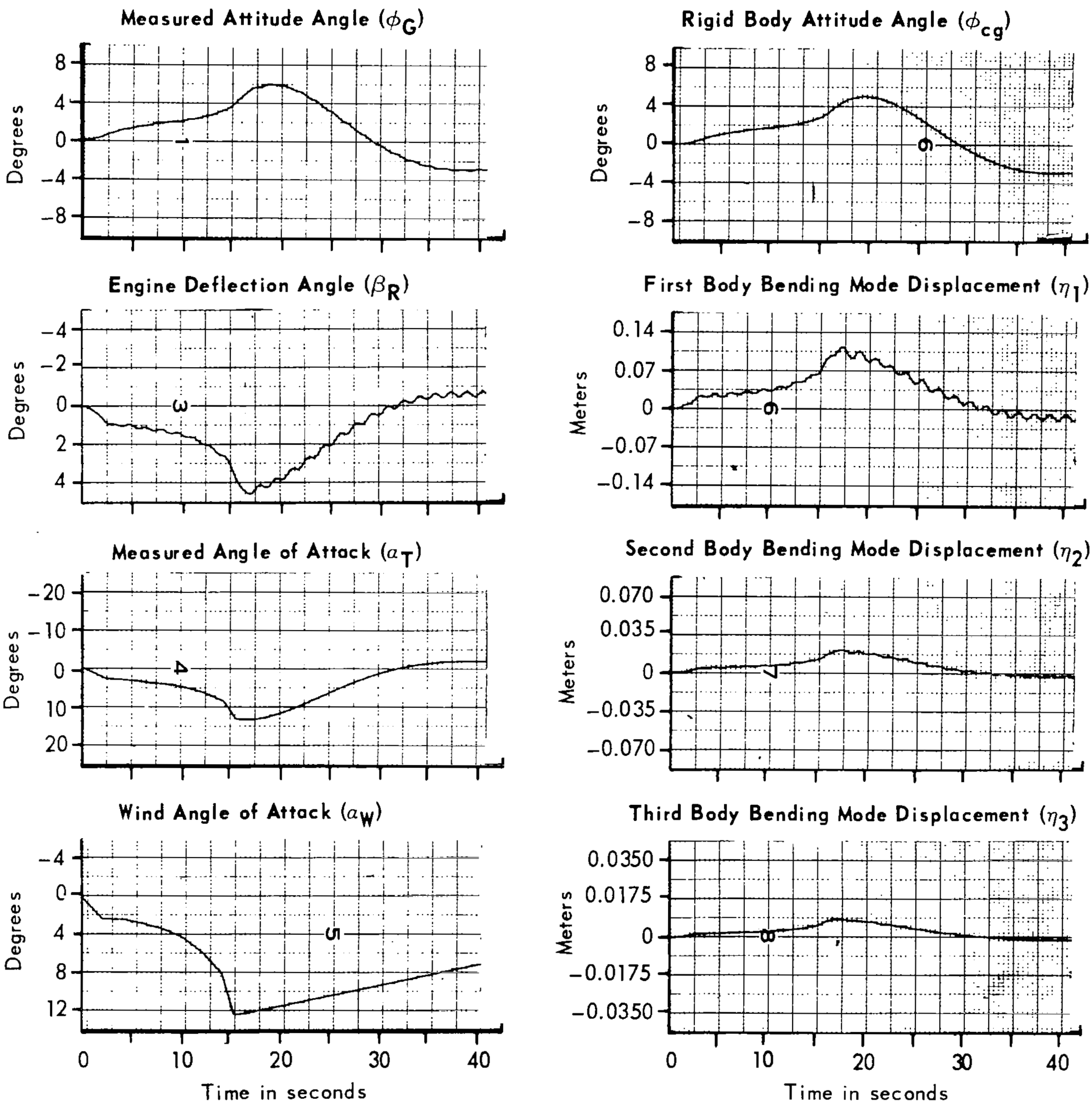


Figure 5 Wind Responseof Study Vehicle No.1 With Attitude and Attitude RateFeedback

1. Flight condition, maximum q
2. Body bending and fuel slosh, out
3. Control system design, 1.1
4. Forward loop gain, K = 1.8

5. Position feedback gain, $K_{\phi} = 1.0$
6. Rate feedback gain, $K_{\dot{\phi}} = 5.0$
7. Acceleration feedback gain, $K_{\ddot{r}} = 0.072$
8. No polynomial fitting in acceleration feedback

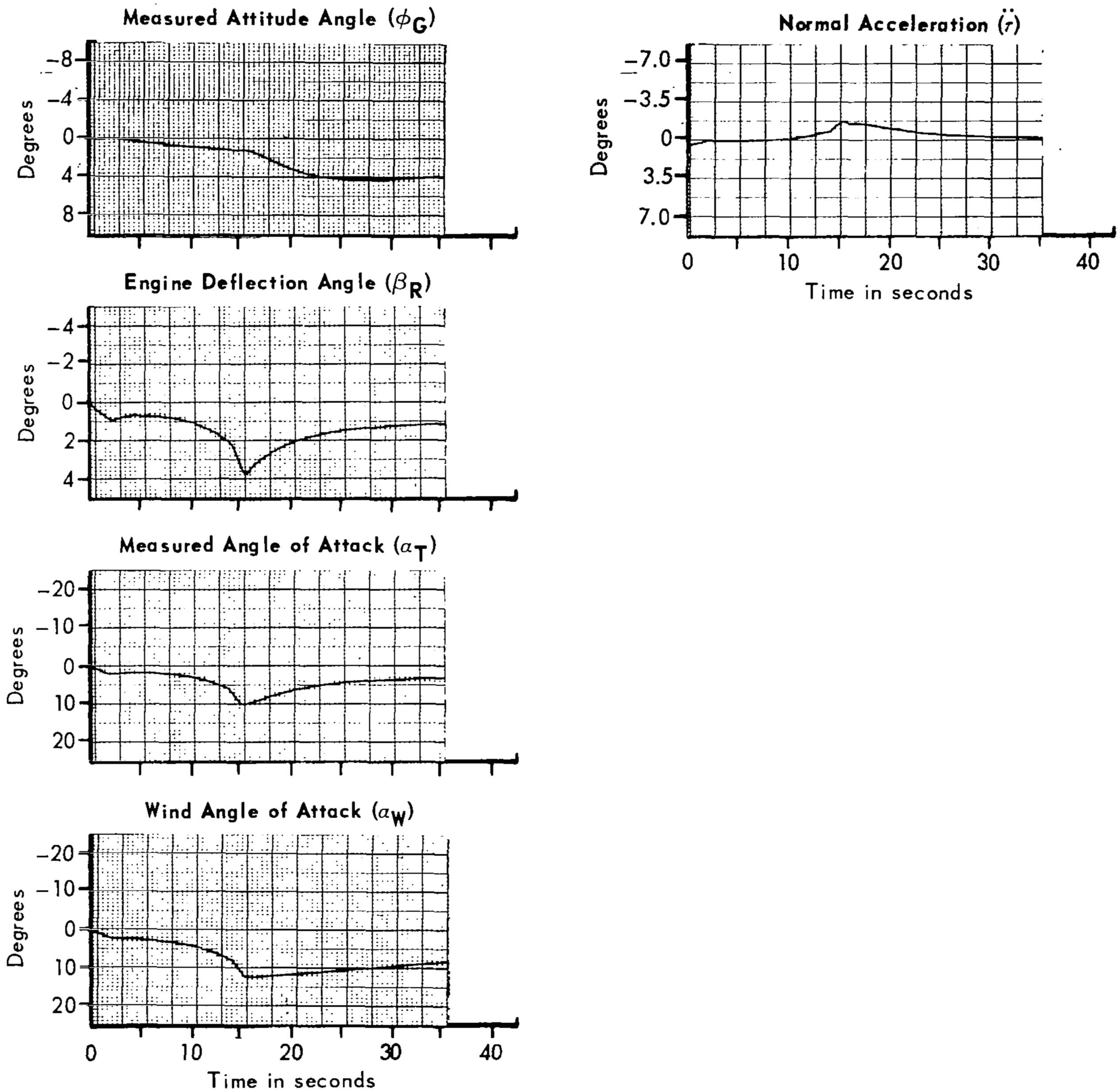


Figure 6 Wind Response of Study Vehicle No. 1 With Bending Modes Removed and Without Filtering inthe Acceleration Feedback Loop

1. Flight condition, maximum q	5. Position feedback gain, K_{ϕ} – 1.0
2. Body bending and fuel slosh, in	6. Rate feedback gain, $K_{\dot{\phi}}$ – 5.0
3. Control system design, I.1	7. Acceleration feedback gain, $K_{\ddot{\tau}}$ = 0.072
4. Forward loop gain, K – 1.8	8. No polynomial fitting in acceleration feedback

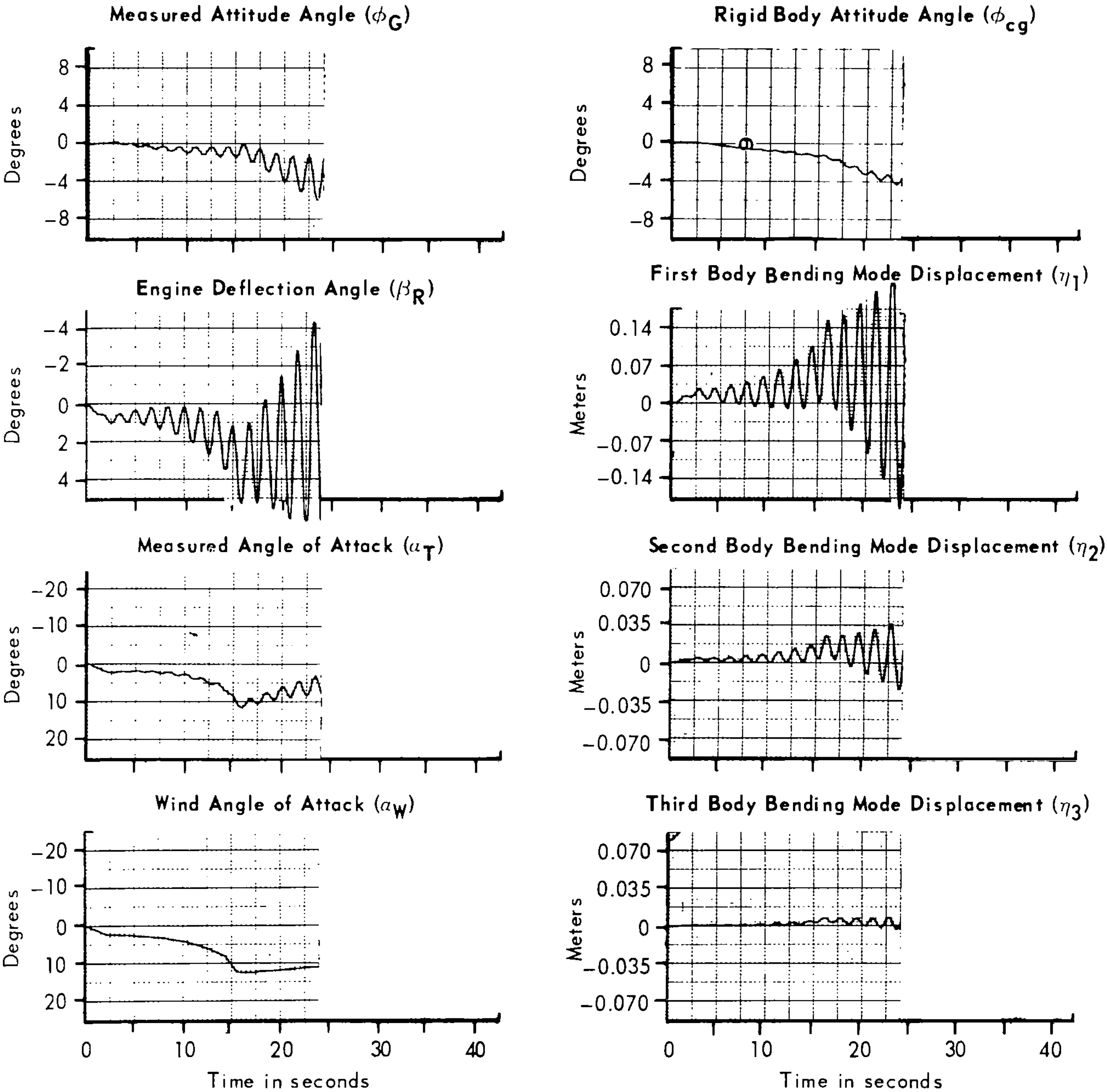


Figure 7 Wind Response of Study Vehicle No. 1 Without Filtering in the Acceleration Feedback Loop

1. Flight condition, maximum q	6. Control system design, I.1
2. Body bending and fuel slosh, out	7. Forward loop gain, K = 1.8
3. Polynomial fitting in acceleration feedback, zero degree (A_O)	8. Position feedback gain, $K_{\phi} = 1.0$
4. Past samples stored, 25	9. Rate feedback gain, $K_{\dot{\phi}} = 5.0$
5. Sample rate, 5 per second	10. Acceleration feedback gain, $K_{\ddot{r}} = 0.072$

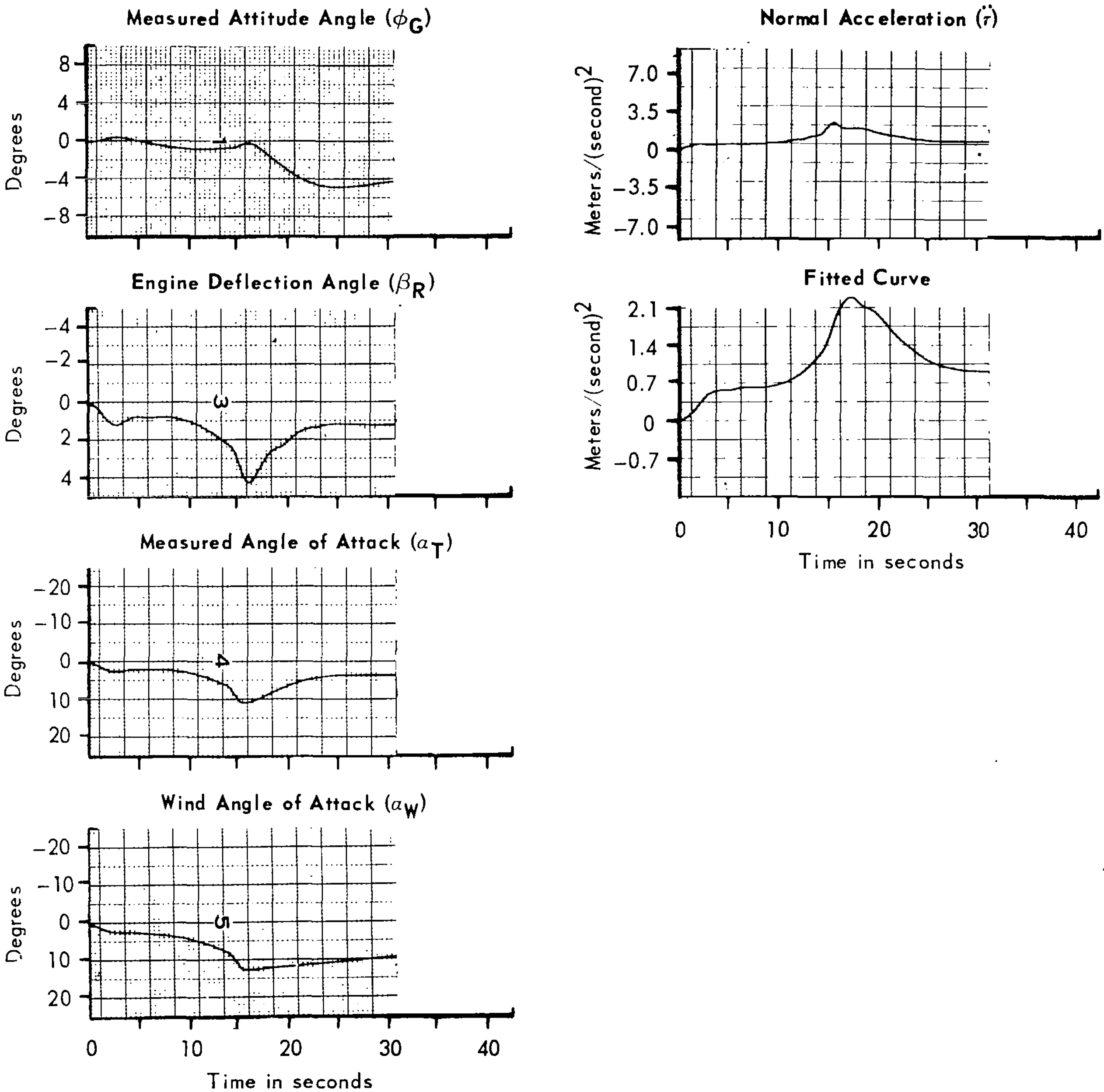


Figure 8 Wind Response of Study Vehicle No. 1 With the Digital Polynomial Filter in the Acceleration Feedback Loop

1. Flight condition, maximum q	6. Control system design, 1.1
2. Body bending and fuel slosh, in	7. Forward loop gain, K = 1.8
3. Polynomial fitting in acceleration feedback, zero degree (A_0)	8. Position feedback gain, $K_{\phi} = 1.0$
4. Past samples stored, 25	9. Rate feedback gain, $K_{\dot{\phi}} = 5.0$
5. Sample rate, 5 per second	10. Acceleration feedback gain, $K_{\ddot{\tau}} = 0.072$
	11. S closed for design 1.1 in Figure 3

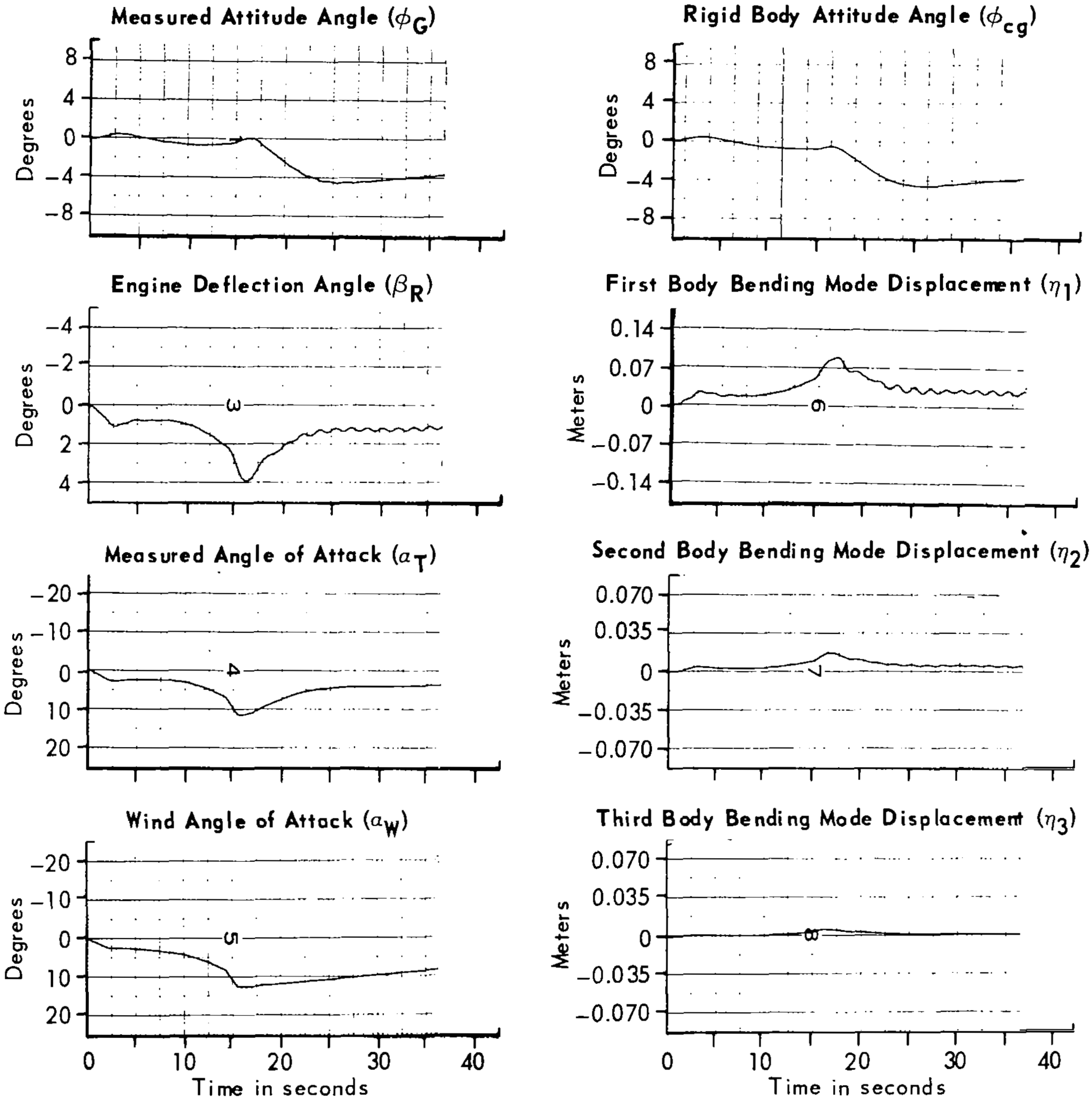


Figure 9 Wind Response of Study Vehicle No. 1 With the Digital Polynomial Filter in the Acceleration Feedback Loop

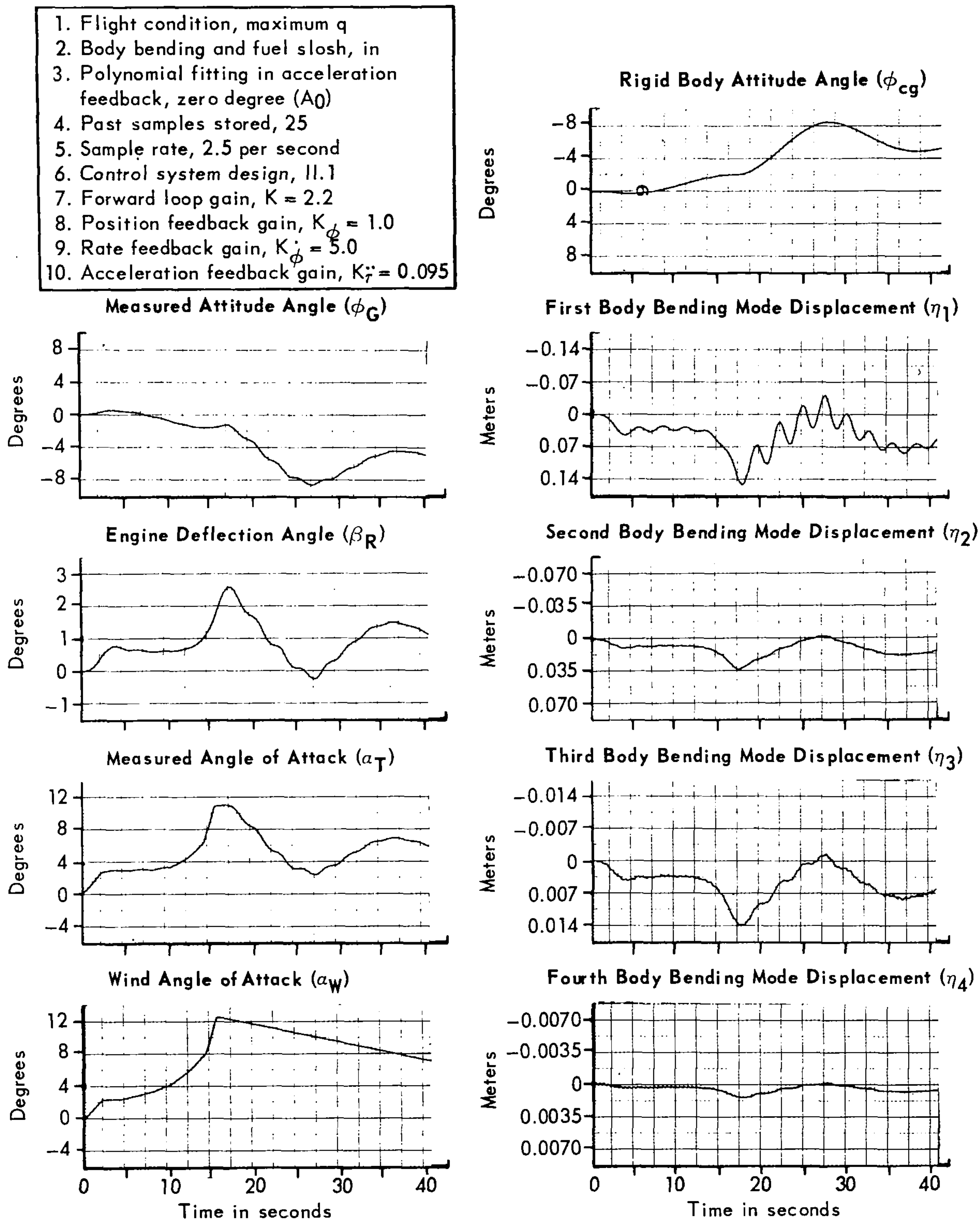
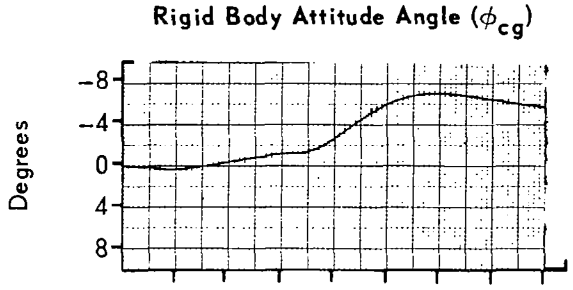


Figure 10 Wind Response of Study Vehicle No. 11 With the Digital Polynomial Filter in the Acceleration Feedback Loop

1. Flight condition, maximum q
2. Body bending and fuel slosh, in
3. Acceleration feedback lag network,

$$\frac{1}{1 + 10S}$$

4. Control system design, 11.3
5. Forward loop gain, $K = 2.2$
6. Position feedback gain, $K_{\phi} = 1.0$
7. Rate feedback gain, $K_{\dot{\phi}} = 5.0$
8. Acceleration feedback gain, $K_{\ddot{r}} = 0.095$



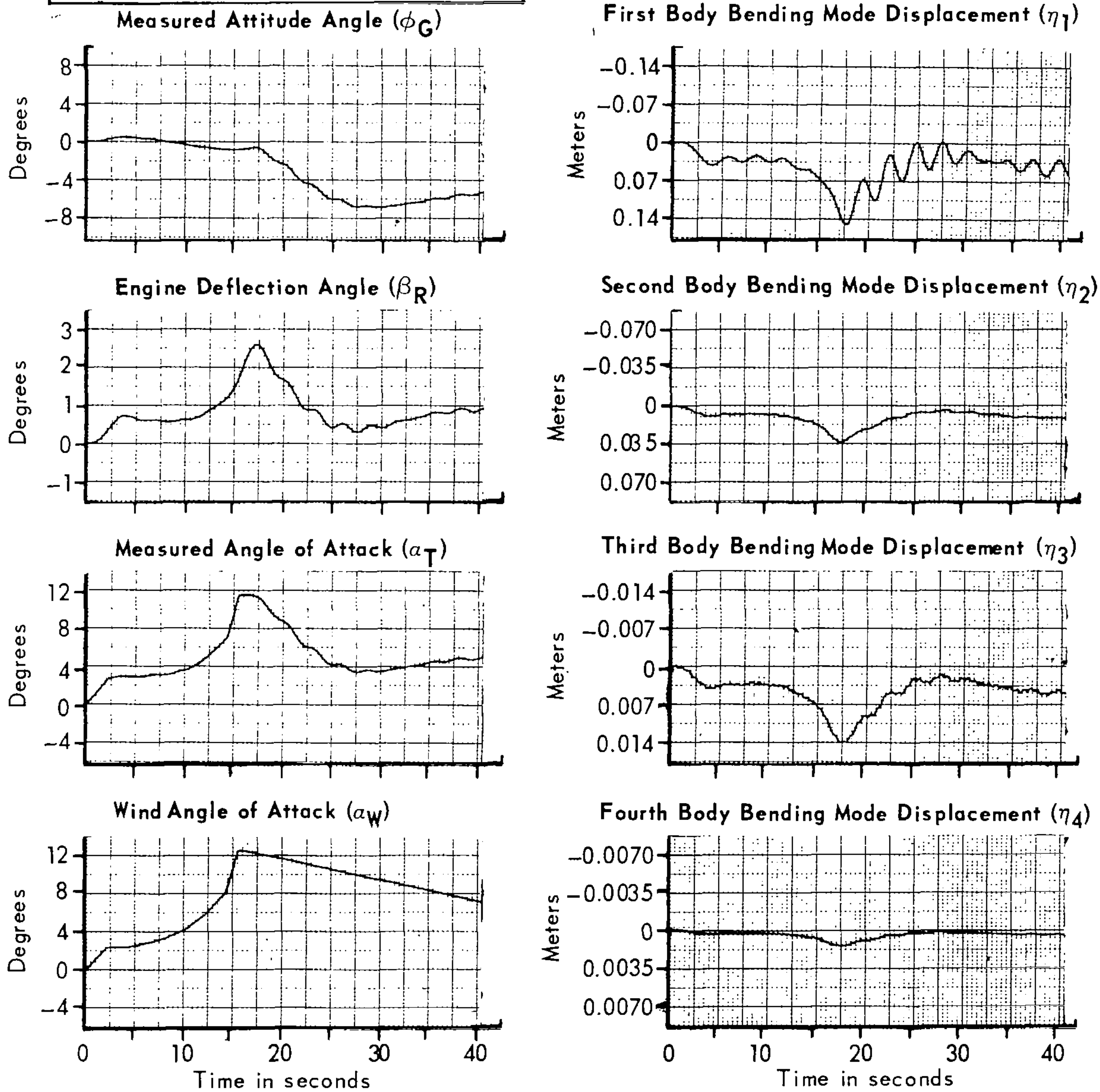


Figure 11 Wind Response of Study Vehicle No. 11 With a Linear Lag Filter in the Acceleration Feedback Loop

Values for the peak angle of attack, α_T, the peak engine deflection angle, β_R, the peak attitude angle, and the end of transient flight path angle have been read from these figures and are summarized in Tables I and II for a concise comparison of these systems.

From Figures 4 through 11 and Tables I and II, it can be seen that:

(a) Attitude-plus-rate feedback alone produces the largest values for α_T and β_R.

(b) The addition of uncompensated acceleration feedback reduces the values of α_T and β_R at the expense of increased attitude deviation angle and introduces a flexible body instability when the slosh and body bending modes are included.

(c) The digital polynomial filter in the acceleration feedback path stabilizes the system while retaining most of the advantages gained through the addition of the acceleration feedback. Comparison of the rigid body results with acceleration feedback shows that the digital polynomial filter does slightly reduce the effectiveness of the acceleration feedback in reducing α_T.

(d) The use of a linear low-pass filter in the acceleration feedback path provides stable system performance comparable with that obtained using the digital polynomial filter.

(e) The studies of the Vehicle II control system, as indicated by Figures 10 and 11, revealed the presence of a low damped oscillation present in the vicinity of the first bending mode and slosh mode frequencies. The only linear compensation which could eliminate this oscillation would be a dipole precisely positioned among the slosh modes and first bending mode. The requirement for accurate knowledge of these modes makes this solution impractical and infers that a slowly damped mode of this type is inherent in any linear compensation of study Vehicle II. If this is unacceptable, it may be necessary to modify the slosh mode frequencies or damping to further separate them from the first bending mode.

Conclusions Regarding the Digital Polynomial Filter

From the results presented here and from the additional results summarized in Reference 1, it was concluded that either digitally or linearly filtered acceleration feedback is effective in providing satisfactory launch vehicle performance in the presence of windshear. Use of the digital polynomial filter may be readily implemented if the control system is already digital in nature. The system using the digital polynomial filter is slightly more sensitive to variations in the bending frequencies than the linear low-pass filter. On the other hand, of the systems studied here, the digital polynomial filter shows somewhat better load relief characteristics.

Table I Summary of Response Characteristics for Study Vehicle I Passing Through a Synthetic Wind Profile

Case No.	Vehicle Description	Control Mode	Peak Angle of Attack, α_T (Degrees)	Peak Engine Deflection Angle, B_R (Degrees)	Peak Attitude Angle, ϕ_T, (Degrees)	Flight Path Angle, θ, at End of Transient ($t = 35$ Sec.) (Degrees)	Response Shown in Figure No.
1	Rigid body only	Attitude and attitude rate feedback	14.0	4.9	6.3	−0.5	4
2	Rigid body plus bending and slosh modes	Attitude and attitude rate feedback	13.5	4.6	6.0	−1.4	5
3	Rigid body only	Attitude, attitude rate and acceleration feedback	10.0	3.6	−4.4	−7.0	6
4	Rigid body plus bending and slosh modes	Attitude, attitude rate and acceleration feedback	System unstable at first body bending mode				
5	Rigid body only	Case 3 with digital polynomial filter in the acceleration feedback	11.0	4.3	−4.8	−7.7 ($t = 30$ Sec)	8
6	Rigid body plus bending and slosh modes	Case 4 with digital polynomial filter in the acceleration feedback	11.5	3.9	−4.6	−7.8	9

Table II Summary of Response Characteristics for Study Vehicle II Passing Through a Synthetic Wind Profile

Case No.	Vehicle Description	Control Mode	Peak Angle of Attack, α_T (Degrees)	Peak Engine Deflection Angle, B_R, (Degrees)	Peak Attitude Angle, ϕ_T, (Degrees)	Flight Path Angle, θ, at End of Transient ($t = 35$ Sec.) (Degrees)	Response Shown in Figure No.
1	Rigid body plus bending and slosh modes	Attitude, attitude rate and acceleration feedback with digital polynomial filter	11.0	2.6	−8.6	−11.2	10
2	Rigid body plus bending and slosh modes	Attitude, attitude rate, and acceleration feedback with linear low pass filter	11.4	2.6	−6.8	−10.4	11

Improving the damping of the first bending and slosh modes of study Vehicle II by means of linear compensation appears impractical; other approaches should be investigated.

It was found that the selection of the various filter parameter values was not critical whether the filter is digital or a linear network, but the time constant of the linear filter or the fitting interval of the polynomial filter must exceed about eight seconds for Vehicle II. The insensitivity to variations of the several control system parameters such as gains and compensation pole-zero locations is quite good. The performance is also sufficiently insensitive to variations in aerodynamic coefficients. The Vehicle II control system is fairly sensitive to bending frequency variations with a tolerance of less than $\pm$ 10% to maintain stability.

THE DIGITAL ADAPTIVE FILTER

A considerable portion of the Reference 1 studies was devoted to establishing the limitations of the digital adaptive filter by applying this control technique to study Vehicles I and II. Because the first bending mode and fuel slosh modes of these study vehicles are at such low frequencies, linear compensation techniques are limited to providing relatively slow response characteristics for large launch vehicles. The digital adaptive filter, however, is designed to separate a well-damped sinusoidal oscillation, such as the rigid body response to a step input, from a mixture of other signals which contain lightly damped oscillations near the rigid body frequency. After the application of a step command, the control loop is effectively closed for the rigid body signal but is essentially open for the elastic and slosh modes. This characteristic permits the digital adaptive filter to produce fast responses to step input commands.

Description of the Digital Adaptive Filter

The digital adaptive filter employs an on-board digital computer. The filter acts on an immediate past section of length T of the signal c(t) stored in the computer memory in a sampled form. This signal is compared with a damped sinusoidal signal ($A\,\epsilon^{-\alpha t}\cos\beta t + B\,\epsilon^{-\alpha t}\sin\beta t$) of fixed frequency β and damping α, and the amplitude parameters A and B (or amplitude and phase) are estimated under the criterion,

$$\min_{A,B} \int_0^T [c(t)-A\epsilon^{-\alpha t}\cos\beta t-B\epsilon^{-\alpha t}\sin\beta t]^2\,dt$$

That is, A and B are calculated to produce minimum mean square deviation between the measured signal and the damped sinusoidal component.

It is assumed that α and β are known fairly accurately. It can be demonstrated that good estimates result for the A and B parameters provided that α and β are within 10-20% of their actual values, that α is relatively large, and that the remaining signal differs widely from the damped sinusoidal component of interest in damping or in frequency but not necessarily in both.

The basic working equations for the digital adaptive filter as applied to study Vehicles I and II were established earlier in Reference 3. The present study revealed that the digital adaptive filter is highly effective in stabilizing the bending and slosh modes. In the quiescent state, however, when there is no control signal and no output of the digital adaptive filter, the rigid body loop is also open, permitting the basic aerodynamic instability to prevail. For this reason, it is necessary to control the vehicle in the quiescent mode by a linear "secondary" filter which provides stability, although it may not give suitable performance in other respects. The digital adaptive filter is then used to provide performance only during transient conditions after a step command. The curve fitting process used by the digital adaptive filter is not fully effective until after the first quarter of a rigid body cycle. For this reason, a second order compensation network is used in the forward loop to help shape the bending mode response during this period.

The basic mode of operation is as follows:

(a) In the quiescent state, the vehicle is under the control of the secondary filter loop which provides a stable but slowly responding system.

(b) The command signal is continually monitored for steps or discontinuities. When a discontinuity is detected, control by the digital adaptive filter commences, with the filter memory length gradually increasing.

(c) After a fixed time interval, vehicle control is returned to the secondary filter since the digital adaptive filter output signal is nearly zero at the end of the response transient.

A block diagram of the digital adaptive filter, as applied to study Vehicle I, is shown in Figure 12. The input to amplifier K_A is the point at which control of the vehicle is switched between the secondary filter and the digital adaptive filter. It should also be noted that the feed-forward network of $\tau s/(\tau s+1)$ and the forward loop network $(1+\tau s)/(1+0.025s)$ in the digital adaptive filter circuit combine to provide the equivalent of a rate feedback control system. This configuration was chosen since it provides the digital adaptive filter with a better signal form to fit, and it eliminates the larger amplitude component of the bending and slosh modes contained in the rate feedback.

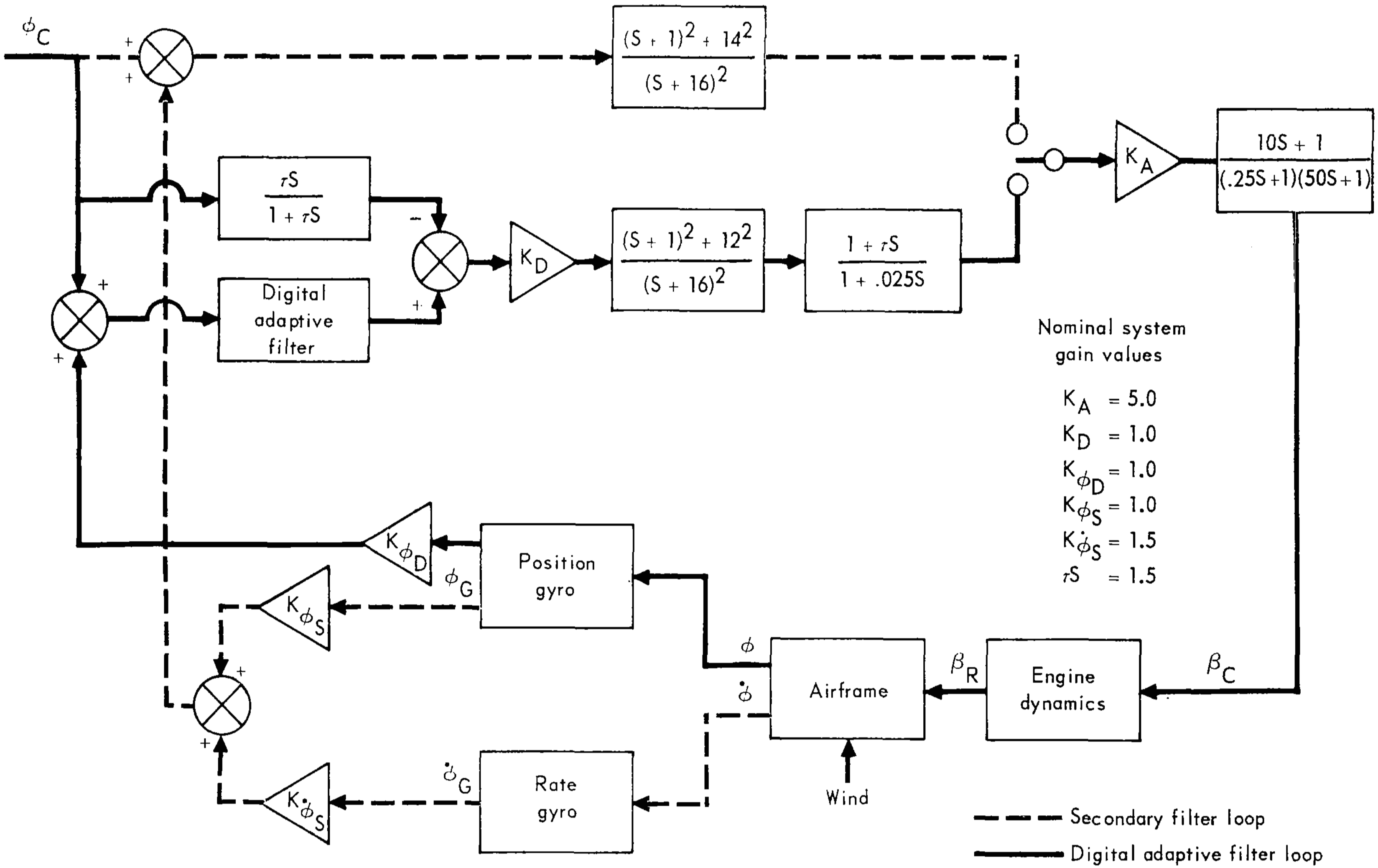


Figure 12 Digital Adaptive Filter Control System Block Diagram for Vehicle 1 at the Lift-Off and Maximum q Flight Conditions

Simulation Test Results

The response of study Vehicle I under the control of the digital adaptive filter was obtained using the hybrid simulation. Typical results for the liftoff flight condition are shown in Figure 13. For a one degree step attitude command, the time to peak response is 3.2 seconds and the overshoot is held to 0.2 degree. In this particular test, the digital adaptive filter was allowed to remain in control throughout the time period shown. It can be seen in this case that after approximately 20 seconds, the output of the filter fades out and the unstable airframe begins to diverge; prior to this time, then, the slower responding but stable secondary filter should be again put in control of the vehicle.

To demonstrate the filtering characteristic of the digital adaptive filter, the same test was repeated with unity gain replacing the digital adaptive filter. The results, which are shown in Figure 14, illustrate the poorly damped system response indicative of body-bending feedback.

When the digital adaptive filter is replaced by a unity gain, the vehicle aerodynamic and bending mode instability becomes more pronounced at the maximum q flight condition, as is illustrated by Figure 15. The corresponding response when using the digital adaptive filter and secondary filter is shown in Figure 16. In this combination run, the digital adaptive filter is started at t=0, the time of initiation of the command step input. The system is under the control of the digital adaptive filter until 3.2 seconds, at which time the secondary filter takes control. This example demonstrates the fast response and elastic stability achievable with the digital adaptive filter, while long range rigid body stability is provided by the secondary filter.

Conclusions Regarding the Digital Adaptive Filter

The digital adaptive filter is a means for improving the transient response to step command inputs to a large launch vehicle typified by study Vehicle I. Results at both liftoff and maximum dynamic pressure show response times of less than 3.2 seconds with acceptable overshoot characteristics. The filter was found to be quite insensitive to parameter variations in the filtering routine, in the compensating circuits, or in the airframe itself.

The digital filter is not designed to reduce excessive stress or excessive engine deflections while the missile is passing through a severe wind profile. For these purposes, the remedies are best achieved through the application of filtered acceleration or angle-of-attack feedback as discussed in the preceding section of this report. The digital adaptive filter is most responsive to step input commands and would thus require resolution of command inputs into a series of steps. Studies required to establish the limits on the step size necessary for discrimination from noise and to evaluate the effect on payload performance were judged by the MSFC sponsors of this study and by McDonnell to have a low probability of demonstrating the applicability of the digital adaptive filter to large launch vehicles. As a consequence, effort was diverted to the study of the digital polynomial filter.

1. Flight condition, lift-off
2. Body bending and fuel slosh, in
3. Damping parameter, $\alpha = 1.8$
4. Frequency parameter, $\beta = 2.2$
5. No secondary filter

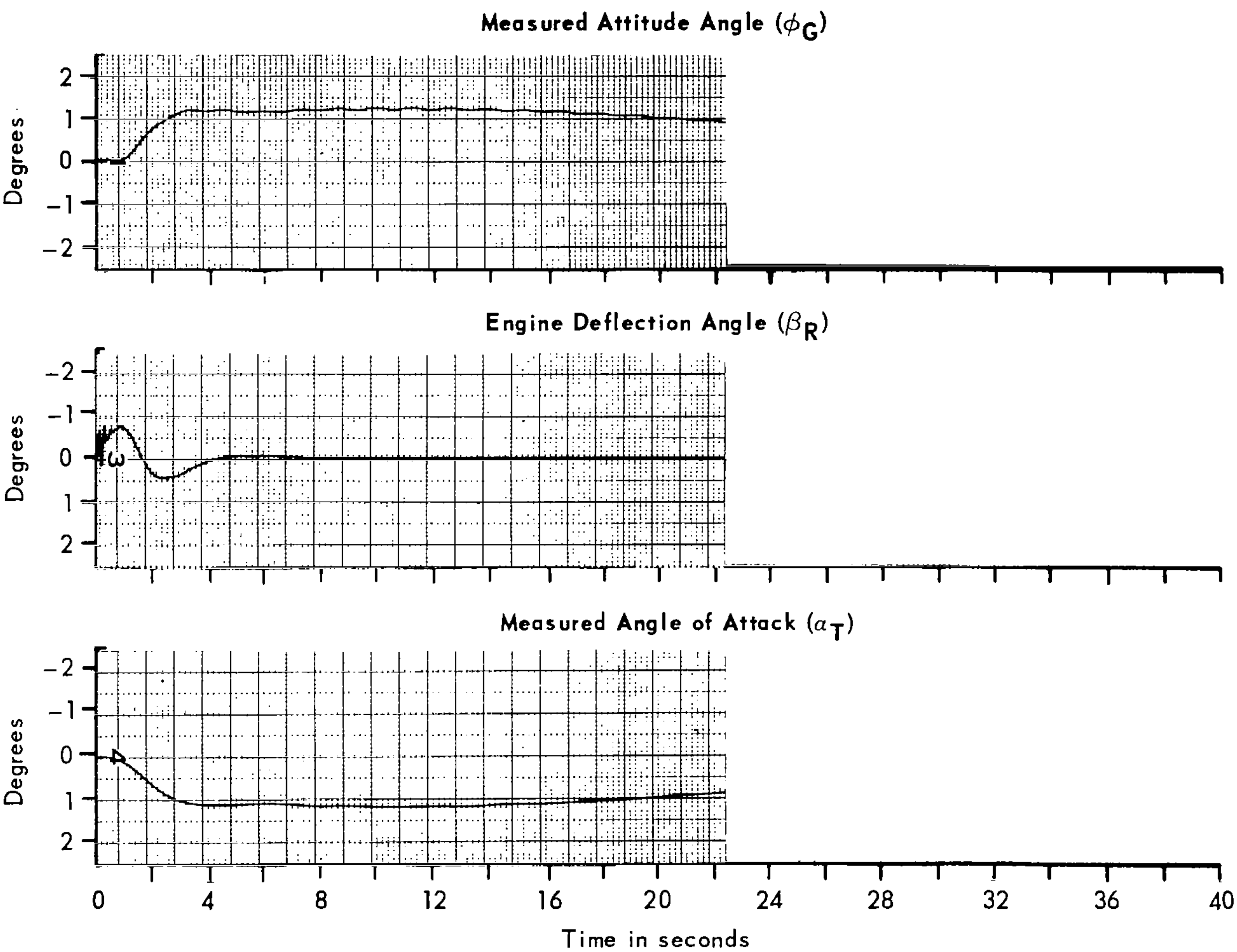


Figure 13 Unit Step Responseof Study Vehicle No. 1

With the Digital Adaptive Filter

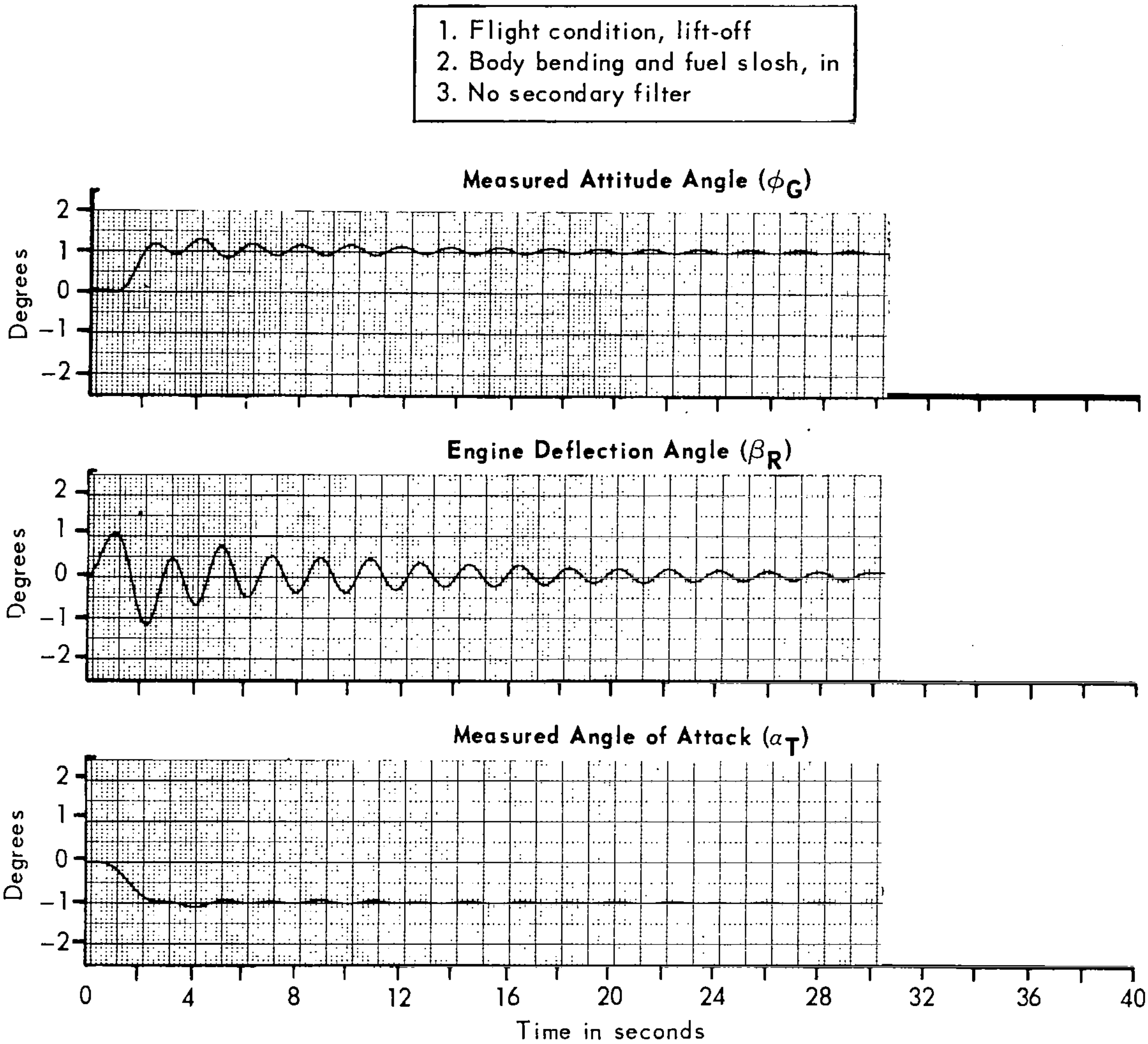


Figure 14 Unit Step Response of Study Vehicle No.1 Without the Digital Adaptive Filter

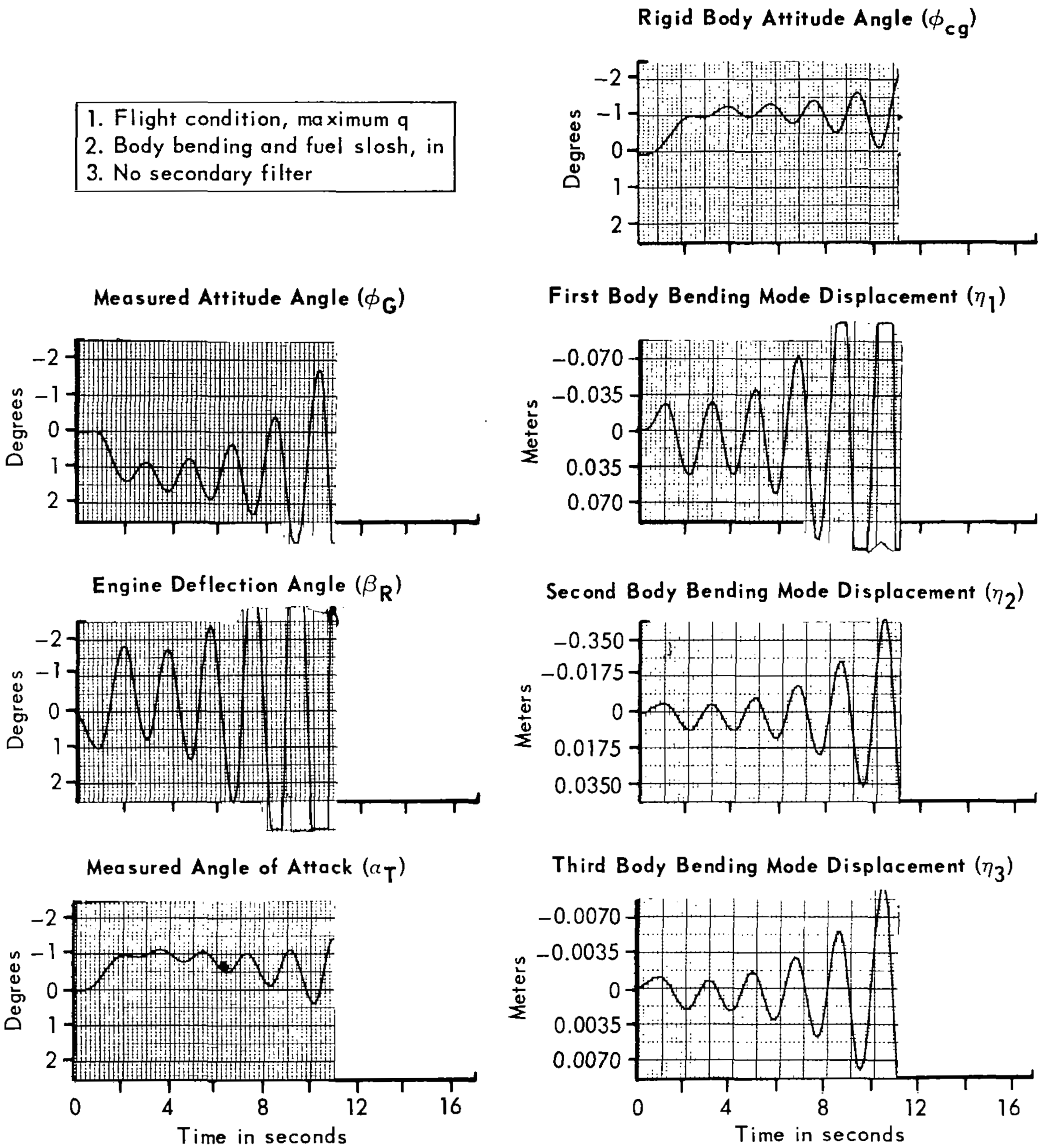


Figure 15 Unit Step Response of Study Vehicle No.1 Without the Digital Adaptive Filter

1. Flight condition, maximum q
2. Body bending and fuel slosh, in
3. Damping parameter, $\alpha = 2.0$
4. Frequency parameter, $\beta = 3.0$
5. Secondary filter switched in at 3.2 seconds

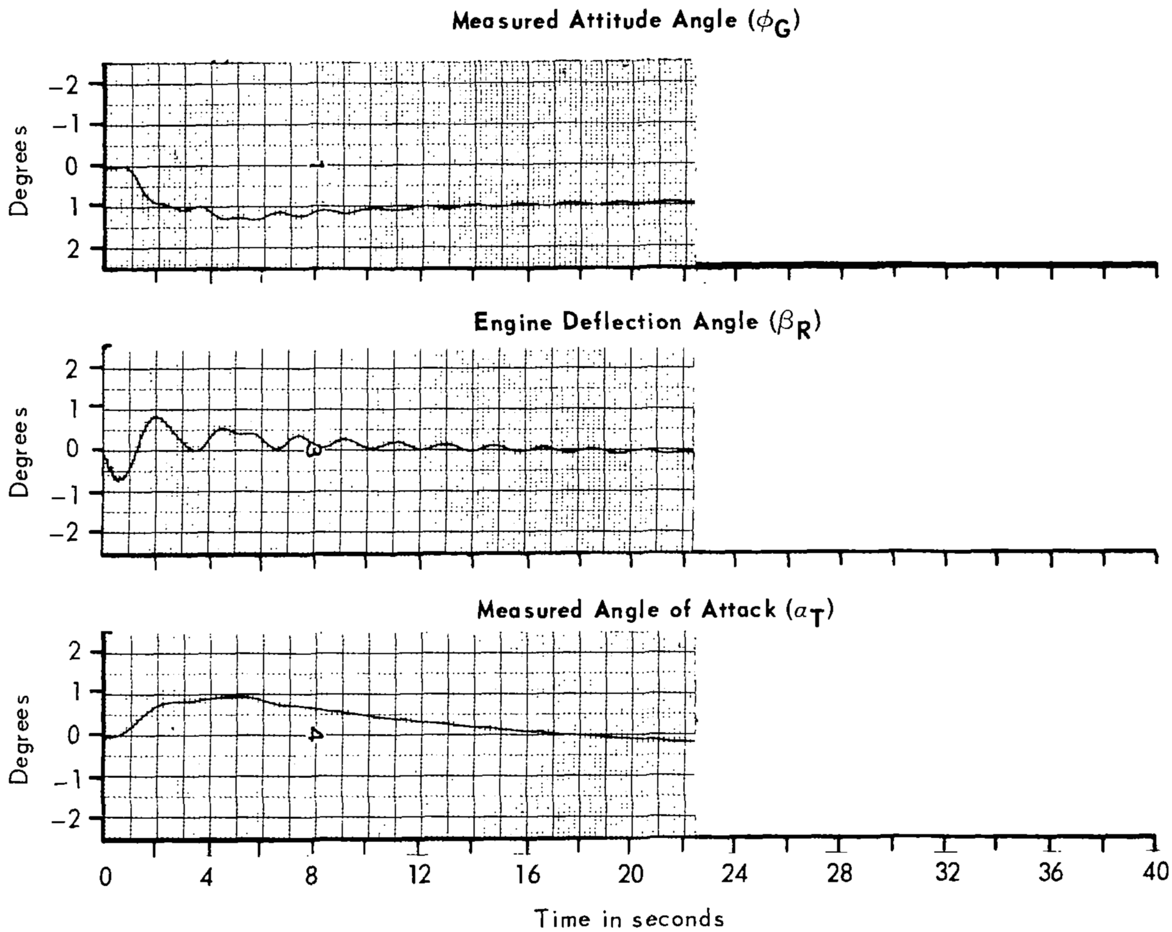


Figure 16 Unit Step Response of Study Vehicle No. 1 With the Digital Adaptive Filter

It should be mentioned finally that these studies do not include an investigation of the burnout flight condition for Vehicle I which presents the additional difficulty of having the first bending mode unstable in the open loop due to cross coupling with the slosh modes. (This open loop bending instability was also present in Vehicle II at the maximum q and burnout flight conditions.) The digital adaptive filter effectively opens up the loop for the bending modes, and if they are stable on an open loop basis, they will ring harmlessly even though their damping may be small. If, however, the bending modes are unstable open loop, the amplitude of the oscillation will build up. Even so, the digital adaptive filter curve fitting process can still operate effectively provided that the stability compensation network keeps the bending mode response from diverging to too large an amplitude before control is switched to the secondary filter. The presence of an open loop instability of the body bending modes precludes the use of periodic restarting of the digital adaptive filter suggested in Reference 3 and places a larger burden on the design of the secondary filter. Another approach suggested by these studies is the use of the residual error signal, the difference between the error signal and the digital filter output signal, for damping of the bending modes through an appropriate network. This type of control, however, was not developed because of the shift of interest in the program from the digital adaptive filter to the digital polynomial filter.

SPECIFICATION SET TYPE COMPENSATION

When an engineer synthesizes a control system, he starts with a knowledge or assumption of the transfer function and a set of performance specifications affecting the accuracy (error constants), damping (damping rates, peak overshoot, height of response peak, etc.), speed (peak time, rise time, resonant frequency), filtering ability (bandwidth), etc., required in the application of this control system. On an elastic booster, some very important components of these specifications are the extent to which the bending modes are excited in a transient, the damping of these modes, and the stresses created in the airframe.

The engineer then proceeds conventionally by cut-and-try techniques (root locus, Nyquist, etc.) to select poles and zeros in the compensating transfer function which will keep the system performance within the set of prescribed specifications. Aside from the cut-and-try approach, this technique has much to recommend it. The specifications included in the set can be tailored to the actual needs and aims of the control system so that they can be truly realistic and representative measures of the vehicle performance. These specifications can be chosen to emphasize the particular aspects of the performance that are of actual concern in the particular design. This method gives not only realism but also flexibility, since none of the specifications is required to be included or excluded. Decision on the selection of the specifications to be used depends exclusively on the need. The difficulty with the practical application of much of modern, optimal, control theory is that the criteria which can be handled mathematically in the solution is too restrictive in nature to define and to incorporate the realistic aspects of good performance meaningfully.

One difficulty with the specification set type linear design is the large amount of intuition which goes into the cut-and-try type design. This fact requires a skilled human operator. Consequently, it is not applicable where the design or redesign must be done continuously as in an on-board adaptive control for a booster. To make the process applicable to this situation, it must first be mechanized. This mechanization was shown to be possible in Reference 4. The specification must be expressed mathematically in terms of the system pole and zero locations. A set of nonlinear equations are obtained which must be solved simultaneously. A solution can be accomplished in an adaptive situation quite efficiently by the use of an iterative linearization technique such as the Newton-Raphson method. The successive parameter corrections are likely to be quite small (usually less than 10%) so search techniques based on local linearization would be efficient. For this technique to be successful, it is essential to find mathematical descriptions for the various items in the specification set which are reasonably manageable in the iteration process. The details of the specification set procedure are summarized in Reference 1.

As presented here, the design is for the equality type of specification, while most of the specifications used currently are of the inequality type; for instance, overshoot less than some fixed number, m. It is definitely possible to extend the specification set work to include the inequality type specifications, but this will require additional development of the technique.

A limited amount of experimental documentation of the specification set parameter adjustment technique has been carried out in the form of two examples, one of which is presented in this abstract of Reference 1. The examples incorporate simulated trajectory runs in the sense that the aerodynamic derivatives, or more directly, the poles and zeros of the airframe transfer function are varied in the manner they would vary on a typical section of the trajectory. The airframe transfer function used is typical of the rigid body of large unstable boosters. The specification set incorporates the velocity error constant, K_V, peak overshoot, m, at the predominant frequency with a step input, and the peak time, T_p, the time interval needed to reach the peak overshoot following a step output.

It must be emphasized that the purpose of these examples is solely to illustrate the mechanics and the effectiveness of the parameter adjustment techniques. The selection of the particular airframe transfer function is incidental. There is no implication that the particular selection of the set of three performance criteria or the particular set of three adjustable parameters is optimum in any sense or that it is even desirable.

Both examples use the loop gain and the rate feedback gain (or rate feedback zero location) for two of the variable parameters. However, Example I, which is presented here, uses a variable forward loop pole for compensation and Example II, which is presented in Reference 1, uses a variable forward loop zero for compensation.

Example I - A list of the assumptions used for Example I are:

(1) Poles and zeros of the airframe transfer function:

pole: $p_1 = 0$. This pole is fixed.

pole: p_2 and p_3 varying as shown in Figure 17a. Note that p_2 is in the right half plane denoting an unstable airframe.

zero: z_1 varying as shown in Figure 17a.

In addition, there is a compensating zero at $z_2 = \zeta_1 = -3.5$ which is held constant, so it is not an adjustable parameter and accordingly, it will be handled as if it were part of the airframe. So, for the example:

Number of plant poles: $n = 3(p_1, p_2, p_3)$

Number of plant zeros: $k = 2(\zeta_1, z_1)$

Number of compensating poles: $J = 1(\pi_1)$

Number of compensating zeros: $I = 0$

Number of feedback zeros: $K = 1$ (ξ_1)

Number of feedback poles: $L = 0$

(2) Specification Set:

Velocity error constant: $K_v \geq 10$

Peak overshoot at the predominant frequency: $m \leq 10\%$

Time to reach peak overshoot: $T_p \leq 2$ seconds

Total number of specifications: $Q = 3$

(3) Variable Parameters:

Loop gain, B

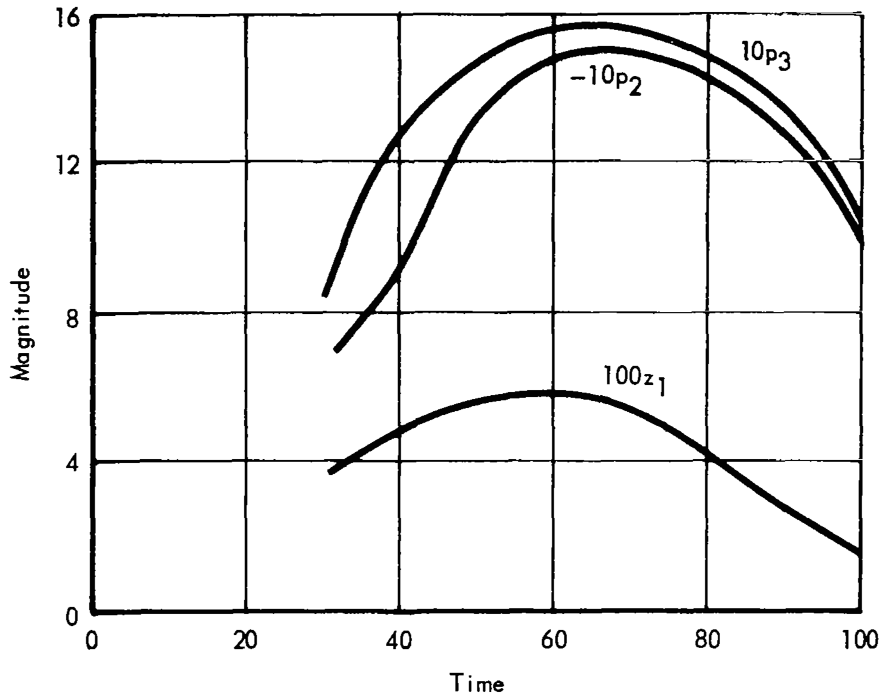
Rate feedback gain, $1/\xi_1$

Forward loop compensating pole or equivalent time constant, π_1

Number of parameters, $J + I + L + K + 1 = 3$ since $L = I = 0$, and $J = K = 1$

Total number of equations, $n + 2L + J + K + I + 1 = 6$

a) Variation with flight time of airframe parameters



b) Variation with flight time of parameters ξ, π and B of compensating networks

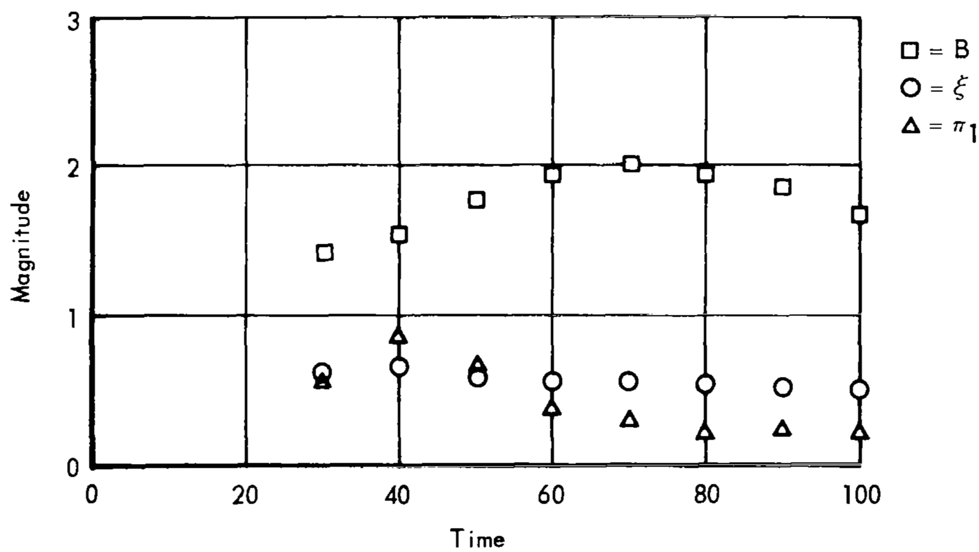


Figure 17 Illustration of Specification Set Parameter Adjustment Process Used in Example 1

The results of the parameter adjustment are shown in Figure 17b. Adjustments were made every ten seconds along the trajectory starting with the previous parameter values. The iteration was carried to very satisfactory accuracy (error at the 10^{-2} - 10^{-3} level) in not more than two steps. One step required less than 0.2 second with a computer program which is not optimized for running time. Optimizing the running time should cut this time to a fraction of the present value.

It can be seen, therefore, that computation of the gain and compensation necessary to meet quantitatively specified performance requirements can be rapdily accomplished. In fact, in view of the rate of change of the airframe variables, the specified performance characteristics can be considered to be met on a near-continuous basis. Of course, to implement the specification set in an on-board system the vehicle airframe parameters must be continuously identified. A possible technique for accomplishing this is presented in Reference 5.

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